NUMERICAL INSPECTION OF CRACK IN SOLID BAR USING CONDUCTION

A Thesis submitted in partial fulfillment of the requirements for the Degree of

Bachelor of Technology
in
Mechanical Engineering
by

Umasankar Sethi
(Roll No- 110ME0257)

Under the guidance of

Dr. Suman Ghosh

Department of Mechanical Engineering
National Institute Of Technology
Rourkela – 769008

National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the research work that has been presented in this thesis entitled "**NUMERICAL INSPECTION OF CRACK IN SOLID BAR USING CONDUCTION**" by Umasankar Sethi (Roll No.110ME0257), has been carried out under my supervision in partial fulfilment of the requirements for the degree of Bachelor of Technology in Mechanical Engineering during session 2013-2014 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this dissertation work has not been submitted in any other college or university at any time prior to this, for the award of any degree or diploma.

Place: Rourkela
Date:

Dr. Suman Ghosh
Assistant Professor
Department of MechanicalEngineering
National Institute of Technology, Rourkela

ACKNOWLEDGEMENT

I would like to thank and express my gratitude towards my supervisor **Dr. Suman Ghosh** for his extensive support throughout this project work. I am greatly indebted to him for giving me the opportunity to work with him and for his belief in me during the hard time in the course of this work. His valuable suggestions and constant encouragement helped me to complete the project work successfully. Working under him has indeed been a great experience and inspiration for me.

I also extend my thanks to the supportive staff of Mechanical Department for providing me necessary facilities to accomplish this project.

Last but not the least; I would like to express my profound gratitude to God and my parents for their blessings and support without which this task could have never been accomplished.

Umasankar Sethi

110ME0257

CONTENTS

ABSTRACT

The nature, behavior and position of a longitudinal crack in a homogeneous slab is investigated using FVM (Finite Volume Method). Effect of the crack on the stationary temperature field around the slab is also investigated. The slab is presumed to have a source subjected to high temperature and the crack surface is specified with two boundary conditions: '**constant heat-flux**' and '**constant-temperature**'. Numerical results are also provided for various positions and different lengths of the crack (with above mentioned boundary conditions) along with two different boundary conditions of the bottom edge of the slab (i.e. bottom edge with constant heat flux and constant temperature). The heat transfer in the slab is assumed to be occurred through conduction only. Using the temperature profiles elsewhere in the slab, one can predict the nature, position and behavior of the crack.

Key words: Heat conduction, Heat flux, Constant temperature, Finite volume method, Anisotropic and isotropic solids, Homogeneous and non-homogeneous solids.

INDEX OF FIGURES

INDEX OF TABLES

Chapter-1: Introduction and literature survey

In this section a brief literature survey has been done after introducing the problem. After that the aims and objectives for the present work have been clearly defined which follows the gaps in the literature.

1.1 Introduction

The anisotropic solids are widely used in the field of engineering and science in recent times. The materials are chosen for various purposes based on their physical properties. The anisotropic materials are generally made by combining two or more isotropic materials. This process of combining two materials sometimes becomes the reason for crack formation in the place of joint due to the difference in physical property of the joining materials. Besides this, cracks are formed in the anisotropic materials due to fatigue, creep, thermal loading and sometimes due to shock loading etc. So it is very essential to know the effect of these defected or crack surfaces on the material's thermal and mechanical properties. For knowing the effect of the crack on the thermal behavior of the crack, heat conduction is widely used. As long as there is no cavity inside the material, there is no chance of another medium for heat transfer. So in that case the heat transfer in the crack can be assumed as pure conduction.

1.2 Literature survey

There many works have been carried out in the field of anisotropic thermo-elasticity which gives solution to the process of heat conduction across cracks or interfaces in anisotropic solids in terms of experimental, numerical and theoretical works. To name a few, Chang et al., (1977) provided theoretical solution for steady-state conduction considering a various types of geometry of an anisotropic bar which are the bar is bounded by a region with two planes, the bar is of infinite length and the bar is of semi-infinite length. Salt et al., (1983) presented a solution for temperature profiles in physical terms for unsteady-state-conduction for various types of composite bars. Milosevic et al. (2003) calculated the thermal diffusivity and thermal-contact-resistance at a time in coatings and solid layers by using flash method in 2D. Shiah et.al, (2006) investigated the effect of the crack in a solid considering the crack as a isotropic medium layer. Milosevic et al., (2003) presented an analytical solution for temperature caused by unsteady conduction in a cylindrical bar which is excited by a short pulse of laser. Zhou et al., (2007) published a paper showing how thermal conductivity is affected by a passage through which heat transfer occurs in composite materials. Ang et al., (2011) proposed a method for solving the axisymmetric conduction numerically which occurs in a nonhomogeneous solid. Clements et al., (1979) presented a mathematical solution of steady-state-conduction with anisotropic solid when a crack is present in the solid.

1.3 Gaps in literature

Though numerous works have been carried out in the field of anisotropic thermo-elasticity, there are not many papers which focus on isotropic or homogeneous materials. And no study has been done on the reverse work i.e. predicting the geometry and position of the barrier using the heat conduction process. So after studying the behavior of the crack with different boundary conditions and different positions of the crack, the results can be implemented in a reverse way to find out the nature, shape and size of crack.

1.4 Aims and objectives

The aim of this project is to investigate the steady state heat conduction across a slab which has a longitudinal crack in it by considering different size of the crack and varying its position relative to the bottom edge. Unlike in practical problems where the crack is generally insulated, here the crack is presumed with two boundary conditions that is constant temperature of 300k and constant heat flux.

Effect of the crack on the stationary temperature field around the slab will also be investigated for various positions and different lengths of the crack (with above mentioned boundary conditions) along with two different boundary conditions of the bottom edge of the slab (i.e. bottom edge with constant heat flux and constant temperature). Using the temperature profiles elsewhere in the slab, one can predict the nature, position and behavior of the crack.

Chapter-2: Problem Formulation

The homogeneous slab has a longitudinal crack in its center. The material of the slab is taken as Aluminum. The temperature variation due to the crack is observed by assuming 2 different conditions of the crack. These are: the crack is specified with **constant heat flux** and **constant temperature of 300k.**

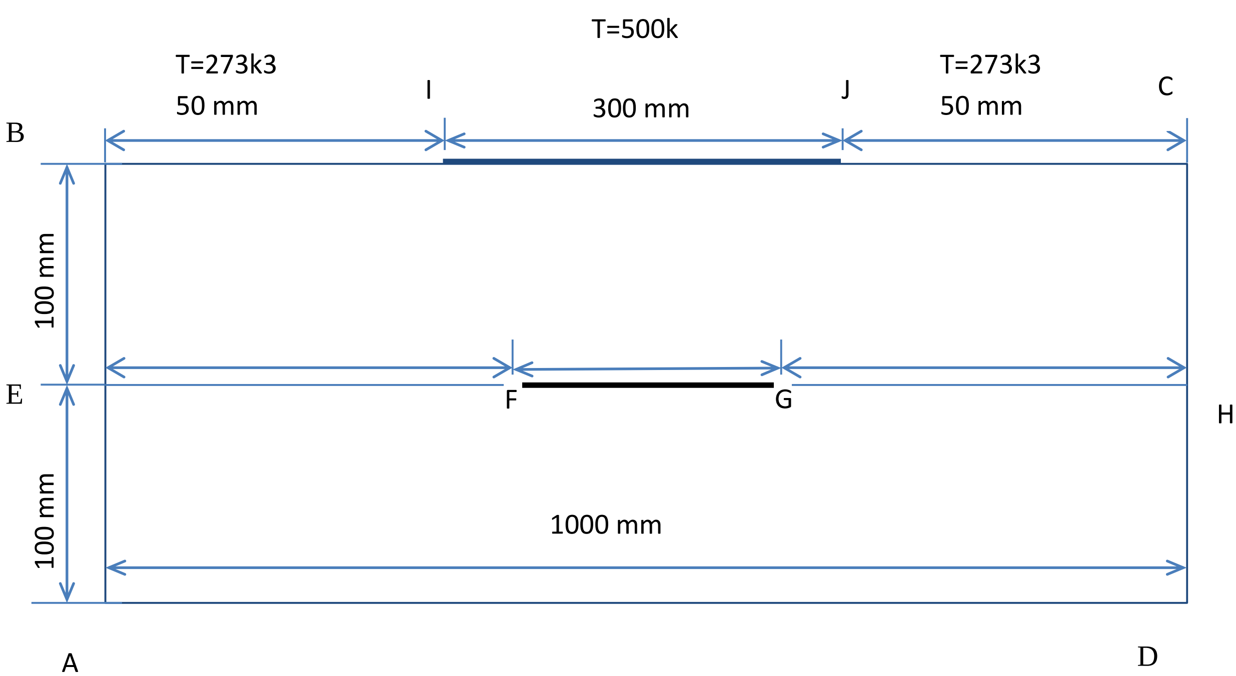


Figure 2.1: Sketch of the problem statement with dimensions and boundary conditions.

The above figure represents the problem statement with necessary dimensions and boundary conditions. The dimensions and the boundary conditions are given below.The dimension of the slab is 1 m x 0.2 m.

AD: bottom edge.

EF & GH: coupled walls.

FG: **crack**, specified with **constant heat flux** and **constant temperature of 300k.**

BI & **JC**: upper zero walls having temperature 273k.

IJ: source having temperature 500k.

AE, **BE**, **CH** & **DH** insulated walls.

Different cases have been observed by:

- **Changing the crack position with respect to the bottom edge.**
- **Changing the crack size.**
- **Changing the boundary conditions of the crack.**
- **Changing the boundary conditions of the bottom edge.**

The cases are explained with proper drawings, temperature contours and temperature profiles in the results section. All the works have been carried in ANSYS software. For better resolution of contours, Tec plot and for plotting the graphs, MATLAB is used. For constant heat flux condition of the bottom edge, the temperature profile is drawn at the bottom edge itself; and for constant temperature (273k) condition of the bottom edge, the temperature profile is drawn at a line present at 0.05m above the bottom edge.

Chapter-3: Methodology adopted

The present project is solely based on results obtained by application of analysis software i.e. ANSYS. The ANSYS software was used for geometric modeling and meshing and the ANSYS solver was used for processing and simulation of the meshing geometries. Quadrangular meshing was employed with grid interval size 0.001. The boundary condition as mentioned in chapter-2, problem formulation is specified and the continuum type is marked as solid. Then the mesh file was processed in the ANSYS solver.

3.1. Numerical calculation and governing equation

The computational approach for the current project is mainly based on the FVM (finite volume method) of two dimensional steady state conduction for which the governing equation comes from the Fourier's law.

That is

$$q_x = -k\frac{dT}{dx}$$

Where *k* is the thermal-conductivity of the material.

and q is the heat-flux.

and *dt/dx* is the gradient of temperature along the direction of heat transfer.

3.2. Residual and convergence

The main purpose for using the residuals are for checking convergence of the solution. ANSYS scales the residuals by using a scaling factor which represents the flow rate of a variable through the entire domain.

In this present study, a fixed value of 0.000001 has been selected for the absolute criteria of continuity, x-velocity, y-velocity and 1e-12 has been selected for the absolute criteria of energy because of the involvement of the smaller grids.

3.3. Method to process the mesh files in ANSYS solver

- Files → read → case files (mesh files)
- Mesh → grid → check
- Define →solver→multiphase (off)
- Define→solver→energy (on)
- Define→solver→viscous→laminar
- Define→materials→solid→Aluminum
- Define→boundary condition→bottom edge(zero heat flux/temperature 273k)

  Coupled walls (coupled)

  Crack (zero heat flux/temperature 300k)

  Insulated walls (zero heat flux)

  Solid slab (aluminium)

  Source (temperature 500k)

  Upper zero walls(temperature 273k)

- Solve→monitors→residuals→0.000001 for continuity, x-velocity and y-velocity, 1e-12 for energy.
- Solve→initialize (from all zones)
- Solve→iterate
- After completion of iteration Display→contours→temperature→total temperature→filled→display.
- Write→case and data files.
- The case and data files are processed in tecplot for better resolution of the contours and processed in MATLAB for plotting the graphs of position vs temperature.

Chapter-4: Results and discussion

This section covers analysis of the following results obtained from the different cases which are followed by some discussions about the results.

4.1 Results Obtained

The results are explained with the help of the temperature contours and graphs. The following 4 cases are studied for 4 different positions of crack i.e. 0.1 m from the bottom edge, 0.125 m from the bottom edge, 0.15 m from the bottom edge and 0.175 m from the bottom edge.

For all the above cases the study has been carried out for different sizes of crack i.e. 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, 0.6 m, 0.7 m, 0.8 m, 0.9 m and 1 m. Contours and graphs of selective cases have been provided here i.e. for 0.1 m, 0.4 m and 0.7 m. The temperature plots for different case have been provided in the corresponding tables in terms of the parameters like mean, standard deviation, skewness and kurtosis.

Mean: The average of a set of values is called as its mean.

Standard deviation: In statistics, standard deviation of a set of values is the deviation of each value from its mean. A lower standard deviation means the values are very close to the average value and a higher standard deviation means the data values are spreading over a large range.

Skewness: It is the measure of asymmetry of a real variable about its mean. It can be +ve, -ve or can be undefined also.

Kurtosis: It is a measure of peakedness of a real valued variable in a probability distribution.

4.1.1 Case-1

The bottom edge is treated as a media with zero heat flux and the crack is also treated as a media with zero heat flux. The source length is 0.3 m and its temperature is fixed i.e. 500k and the side walls are assumed insulated. The crack is placed at 4 different positions relative to the bottom edge. The subcases are explained in the following sections with appropriate figures.

4.1.1.1 Crack position: 0.1m from the bottom edge

When the crack is present at the middle of the slab and smaller in size, there are a lot of spaces except the crack region for heat transfer to take place to the other side of the crack. But as the crack size increases, the heat transfer is gradually blocked by the crack as the crack is specified with constant heat flux. These things are clearly visible from the figure 4.1.

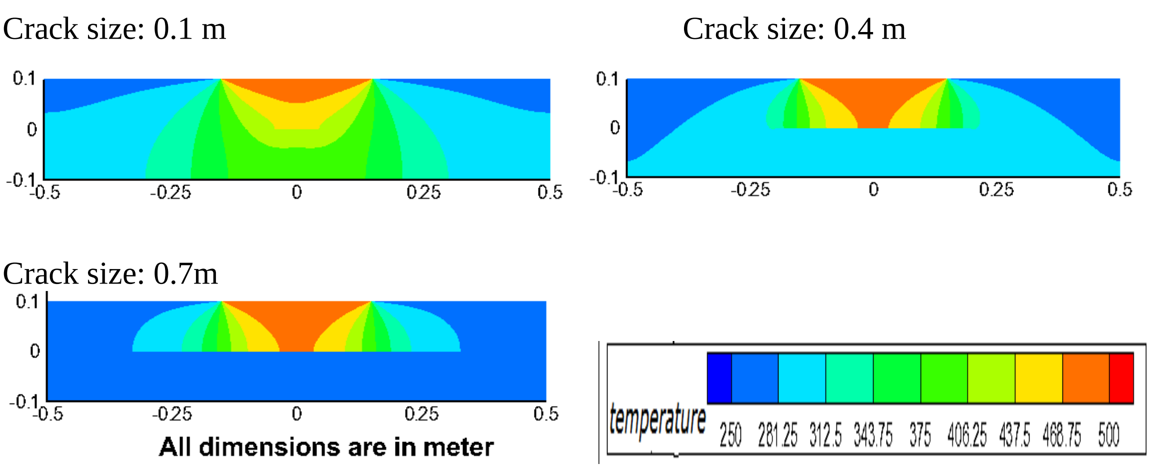


Figure 4.1**:** Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.1 m from bottom edge for **case-1.**

Table 4.1: Temperature profile at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.1 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-1 (Data by treating crack as an media with zero heat flux).

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.1	0.3	0.1	337.4972	40.9150	0.3200	1.5495
0.1	0.3	0.2	326.7900	31.5474	0.1755	1.4282
0.1	0.3	0.3	310.6418	19.0967	-0.0433	1.3560
0.1	0.3	0.4	295.2452	9.0154	-0.3145	1.4316
0.1	0.3	0.5	285.0583	3.5630	-0.6154	1.7146
0.1	0.3	0.6	279.4053	1.2098	-0.9409	2.2498
0.1	0.3	0.7	276.4720	0.3315	-1.2964	3.1047
0.1	0.3	0.8	275.0168	0.0599	-1.2782	4.3413
0.1	0.3	0.9	274.3592	0.0036	-2.0369	5.8141
0.1	0.3	1.0	341.1000	2.2749e-12	1	1

From the results given in Table 4.1, it is noticed that the mean temperature along the bottom edge decrease at a uniform rate until a specific crack length but after that the rate is not uniform. And as long as the crack size is less than the source size, the skewness is positive and after tthat the skewness is negative. When the crack is of 1.0 m that is through the entire length of the slab, the mean temperature is very large and standard deviation is negligible and skewness and kurtosis obtained are perfect 1.

The results obtained for the crack lengths 0.1 m, 0.4 m, 0.7 m from the Table 4.1 are represented graphically as position VS temperature in figure 4.2. it is clearly visible from the figure that for decreasing crack length the temperature gradually increase at the bottom edge.

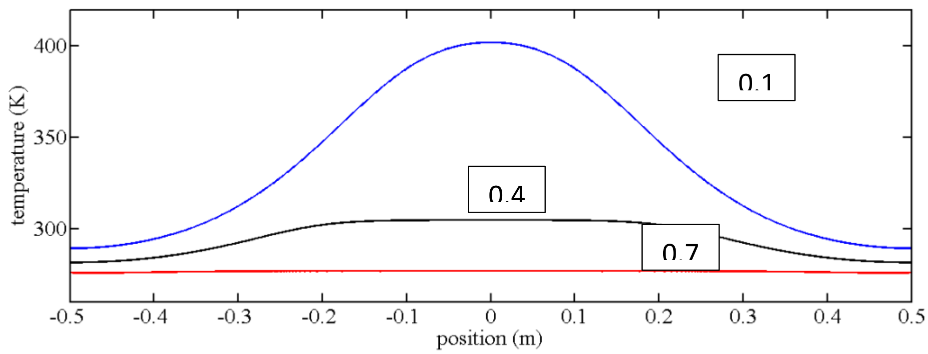


Figure 4.2: Position vs. temperature plot at bottom edge for for crack position at 0.1 m from the bottom edge for crack sizes 0.1 m, 0.4 m and 1.0 m.

4.1.1.2 Crack position: 0.125 m from the bottom edge

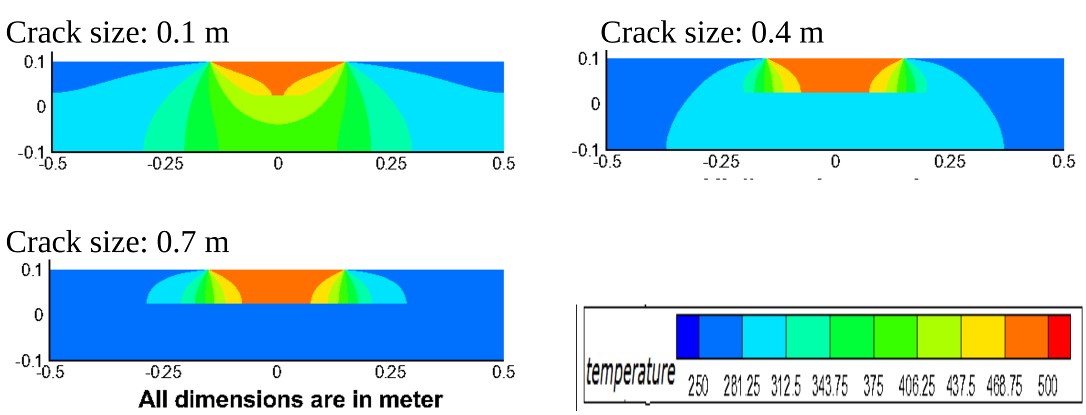


Figure 4.3: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.125 m from bottom edge for case-1.

When the crack is smaller in size, there are a lot of spaces except the crack region for heat transfer to take place to the other side of the crack. But as the crack size increases, the heat transfer is decreases and gradually blocked by the crack as the crack is specified with constant heat flux. These things are clear from the figure 4.1.

Table 4.2: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.125 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-1.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	std	skewness	Kurtosis
0.125	0.3	0.1	336.6239	40.4478	0.3275	1.5606
0.125	0.3	0.2	323.4914	29.8836	0.2015	1.4543
0.125	0.3	0.3	303.7002	15.8111	-0.0027	1.3750
0.125	0.3	0.4	287.1783	5.8341	-0.2675	1.4256
0.125	0.3	0.5	278.8771	1.7685	-0.5566	1.6666
0.125	0.3	0.6	275.3995	0.4662	-0.8589	2.1212
0.125	0.3	0.7	274.0032	0.1006	-1.1721	2.8101
0.125	0.3	0.8	273.4519	0.0146	-1.4862	3.7174
0.125	0.3	0.9	273.2435	8.8890e-04	-1.6983	4.6530
0.125	0.3	1.0	341.1000	2.2749e-12	1	1

From table 4.2 it is clear that when the crack size becomes larger than the source size, the change in the mean temperature is more but there on the change is nearly constant. From table 4.2 it is also noticed that for smaller crack size the skewness of the plot is positive and for larger crack size the skewness is negative. The position VS temperature graphs are plotted at bottom edge for crack size 0.1 m, 0.4 m and 0.7 m in figure 4.4.

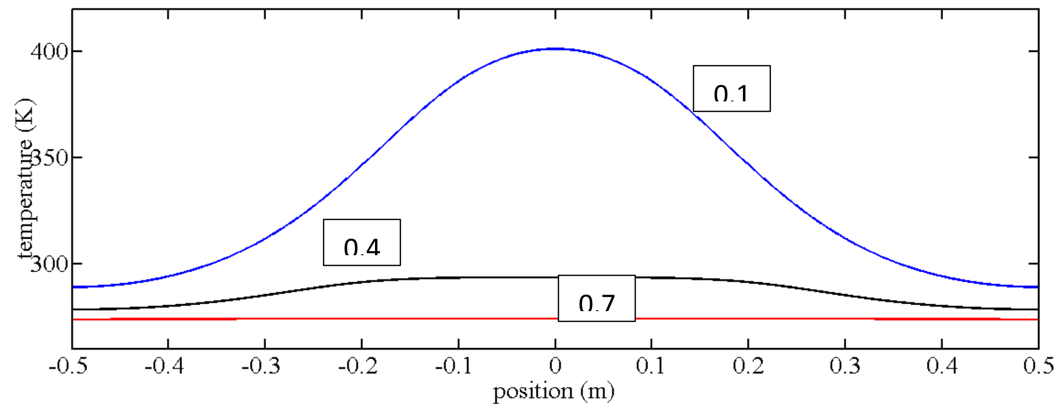


Figure 4.4: Position vs. temperature plot at bottom edge.

4.1.1.3 Crack position: 0.15m from the bottom edge

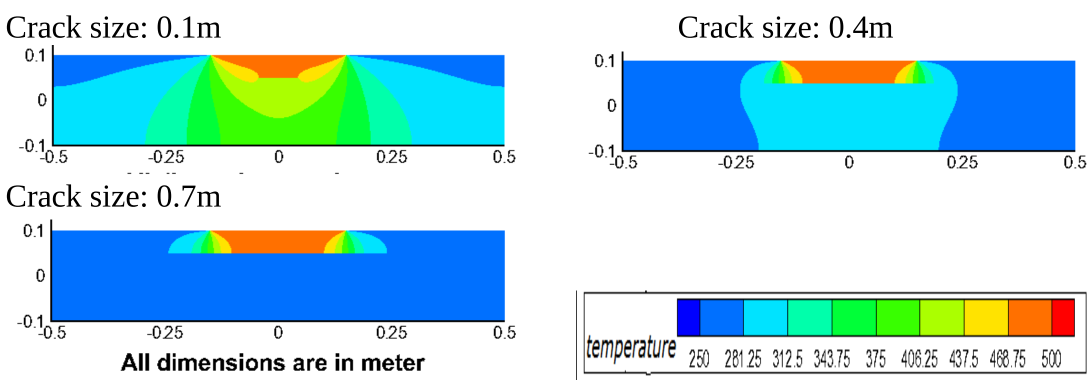


Figure 4.5: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.15 m from bottom edge for case-1.

The crack is placed at 0.175 m from the bottom edge which is very close to the source. So it is clear from the figure 4.5 that for larger size of the crack, the heat transfer is totally blocked to the other side of the crack. The temperature range at different regions can be predicted from the temperature range image from the figure 4.5.

Table 4.3: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.15 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-1.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge			
			Mean	Std	Skewness	Kurtosis
0.15	0.3	0.1	335.9661	40.1636	0.3361	1.5715
0.15	0.3	0.2	320.8418	28.7575	0.2351	1.4846
0.15	0.3	0.3	296.1427	12.2679	0.0537	1.3990
0.15	0.3	0.4	279.4490	2.7433	-2.2042	1.4165
0.15	0.3	0.5	274.5719	0.4947	-0.4802	1.6062
0.15	0.3	0.6	273.3801	0.0790	-0.7601	1.9764
0.15	0.3	0.7	273.0941	0.0105	-1.0419	2.5209
0.15	0.3	0.8	273.0253	0.0011	-1.1916	2.9057
0.15	0.3	0.9	273.0083	4.4710e-04	1.0037	2.0075
0.15	0.3	1.0	341.1000	2.2749e-12	1	1

The standard deviation varies widely for smaller crack sizes but when the crack size becomes greater than the source size, the change in standard deviation is very less. The results can be predicted from table 4.3. As compared to figure 4.4 the figure 4.6 shows some changes in the graph drawn for crack size of 0.4. the temperature curve is more straighter for crack position 0.15 m from the bottom edge.

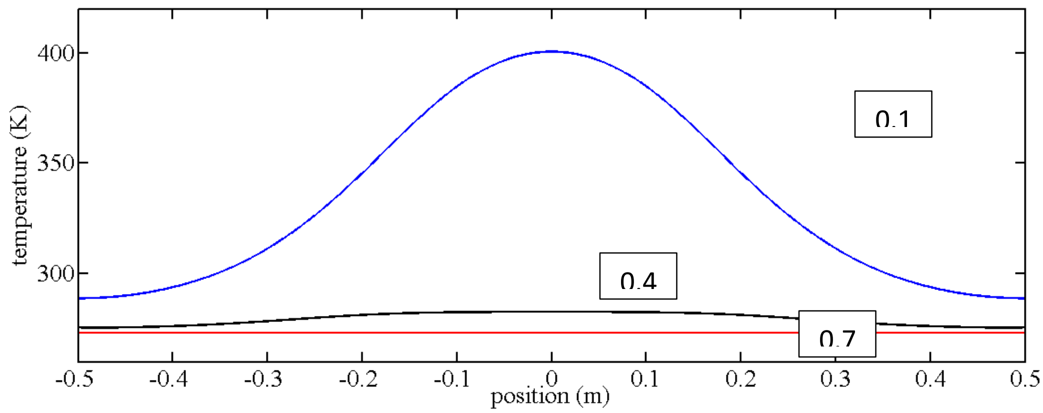


Figure 4.6: Position vs. temperature plot at bottom edge.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.15m from the bottom edge is represented in figure 4.6.

4.1.1.4 Crack position: 0.175m from the bottom edge

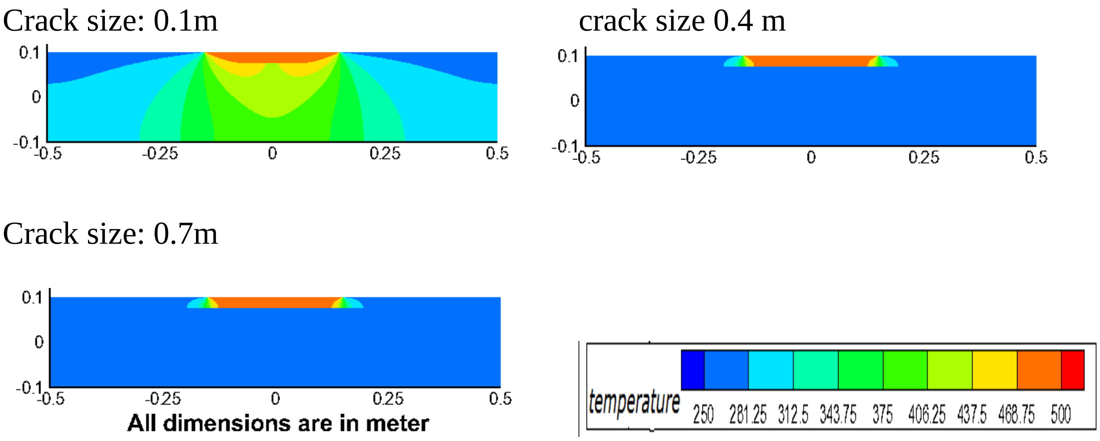


Figure 4.7: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.175 m from bottom edge for case-1.

Here the crack is placed at 0.175 m from the bottom edge. This position is very close to the source. So in this case, for smaller crack lengths, heat transfer is possible to the other side of the crack but for larger crack size heat transfer is not possible to the lower side. It is because as the distance between the crack and source is very small, the region bounded by this two act like a single source for larger crack size.

Table 4.4: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.175 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-1.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.175	0.3	0.1	335.9840	40.3442	0.3450	1.5816
0.175	0.3	0.2	320.4050	29.0785	0.2731	1.5178
0.175	0.3	0.3	287.6977	8.1498	0.1280	1.4337
0.175	0.3	0.4	273.8651	0.3886	-0.1222	1.4094
0.175	0.3	0.5	273.0439	0.0149	-0.3811	1.5402
0.175	0.3	0.6	273.0024	7.3651e-04	-0.6986	2.1450
0.175	0.3	0.7	273	0	NaN	NaN
0.175	0.3	0.8	273	0	NaN	NaN
0.175	0.3	0.9	273	0	NaN	NaN
0.175	0.3	1.0	341.1000	2.2749e-12	1	1

From table 4.4 it is noticed that when the crack size becomes the double the source size there is no heat transfer towards the lower side of the crack and the temperature plots are pure straight lines as can be concluded from figure 4.8.

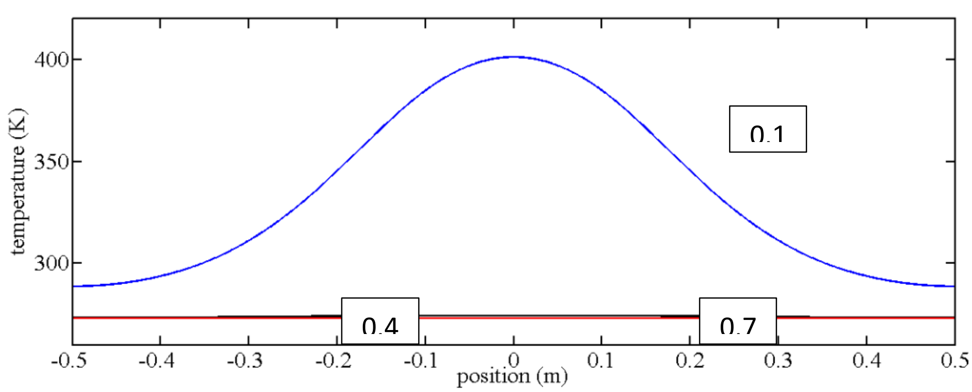


Figure 4.8: Position vs. temperature plot at bottom edge.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.175m from the bottom edge is represented in figure 4.8.

4.1.2 Case-2

For this case the bottom edge is treated as a media with zero heat flux and the crack is treated as a media with constant temperature. The source temperature is fixed i.e. 500k and the side walls are assumed insulated. The crack is placed at 4 different positions relative to the bottom edge. The subcases are explained in the following sections with appropriate figures.

4.1.2.1 Crack position: 0.1m from the bottom edge

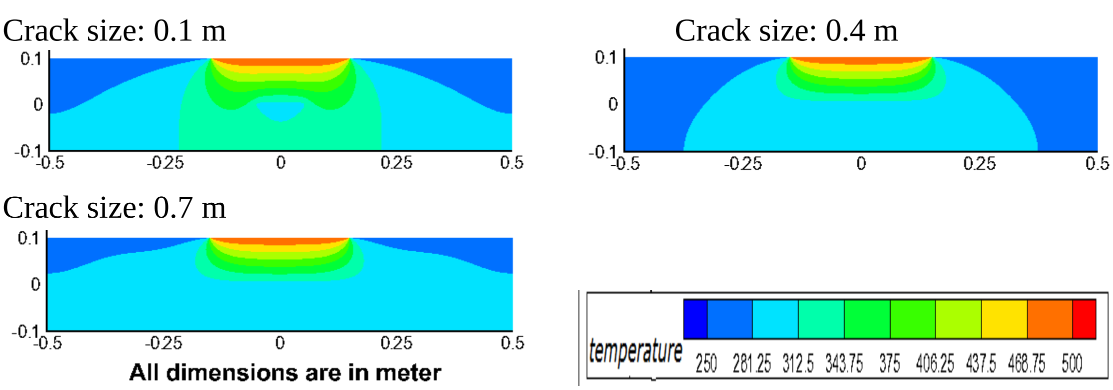


Figure 4.9: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.1 m from bottom edge for case-2.

When the crack is present at the middle of the slab and smaller in size, there are a lot of spaces except the crack region for heat transfer to take place to the other side of the crack. But as the crack size increases, it does not affect much on the temperature field as the crack is an isothermal source here. This can be noticed from figure 4.9.

Table 4.5: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.1 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-2. (Data by treating crack as an Isothermal source)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.1	0.3	0.1	305.5395	16.3141	-0.0749	1.3579
0.1	0.3	0.2	295.0215	10.0660	-0.1993	1.3726
0.1	0.3	0.3	289.9277	8.0301	-0.1131	1.3722
0.1	0.3	0.4	289.5212	7.9145	-0.0852	1.3838
0.1	0.3	0.5	291.3287	7.4648	-0.2867	1.4436
0.1	0.3	0.6	293.6928	6.3025	-0.5598	1.6859
0.1	0.3	0.7	296.0274	4.5661	-0.8552	2.1459
0.1	0.3	0.8	298.0505	2.5336	-1.1552	2.8271
0.1	0.3	0.9	299.4741	0.7492	-1.4157	3.6021
0.1	0.3	1.0	300	0	NaN	NaN

The mean temperature is not changing much at the bottom edge as can be observed from table 4.5. The skewness obtained is negative for all crack sizes. It is mainly due to the reason that the crack is specified with constant temperature.

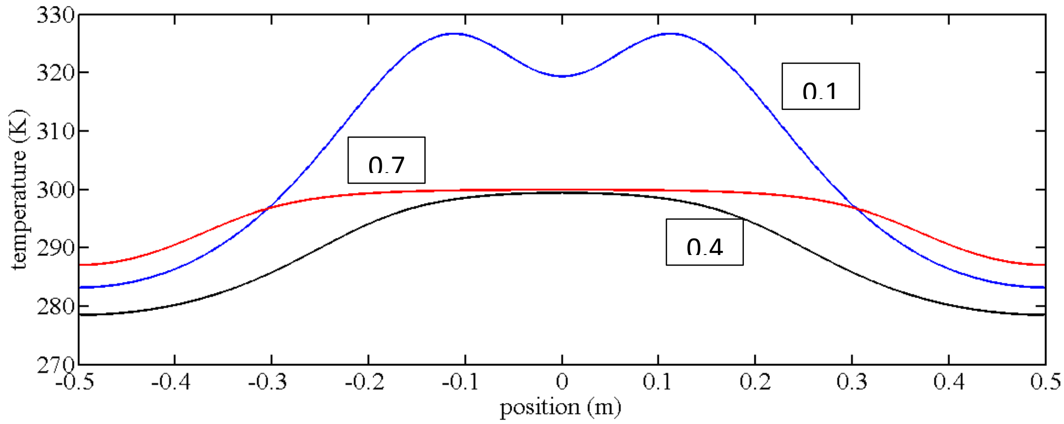


Figure 4.10: Position vs. temperature plot at bottom edge for figure 4.13.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.1m from the bottom edge is represented in figure 4.10.

4.1.2.2 Crack position: 0.125m from the bottom edge

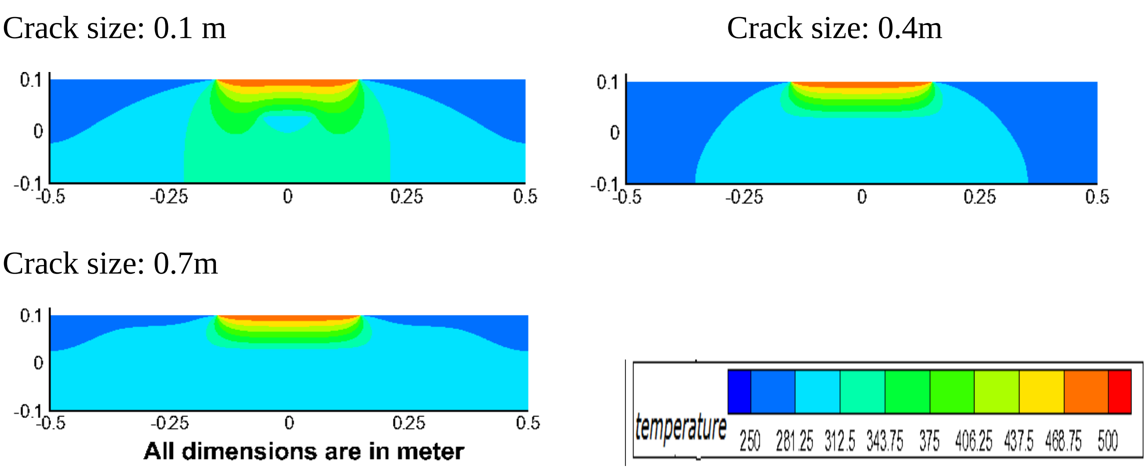


Figure 4.11: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.125 m from bottom edge for case-2.

Table 4.6: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.125 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-2.(Data by treating crack as an Isothermal source)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.125	0.3	0.1	306.3186	17.4562	-0.0148	1.3427
0.125	0.3	0.2	294.0519	10.1536	-0.1253	1.3450
0.125	0.3	0.3	288.1750	7.7888	0.0170	1.3978
0.125	0.3	0.4	288.2597	7.6988	9.3924e-04	1.4017
0.125	0.3	0.5	290.4934	7.2772	-0.2165	1.4387
0.125	0.3	0.6	293.0275	6.2028	-0.4697	1.6255
0.125	0.3	0.7	295.4783	4.5816	-0.7245	1.9669
0.125	0.3	0.8	297.6677	2.6268	-0.9630	2.4293
0.125	0.3	0.9	299.3273	0.8146	-1.1488	2.8894
0.125	0.3	1.0	300	0	NaN	NaN

From table 4.6 it is noticed that the rate of change of standard deviation of temperature is less when the difference between source length and crack length is less. But it is the change is appreciable when the difference between source and crack length increases gradually.

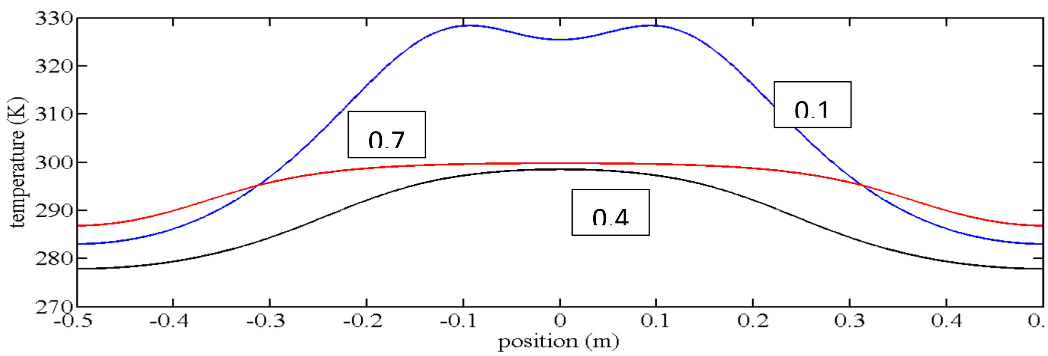


Figure 4.12: Position vs. temperature plot at bottom edge for figure 4.16.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.125m from the bottom edge is represented in figure 4.12

4.1.2.3 Crack position: 0.15 m from the bottom edge

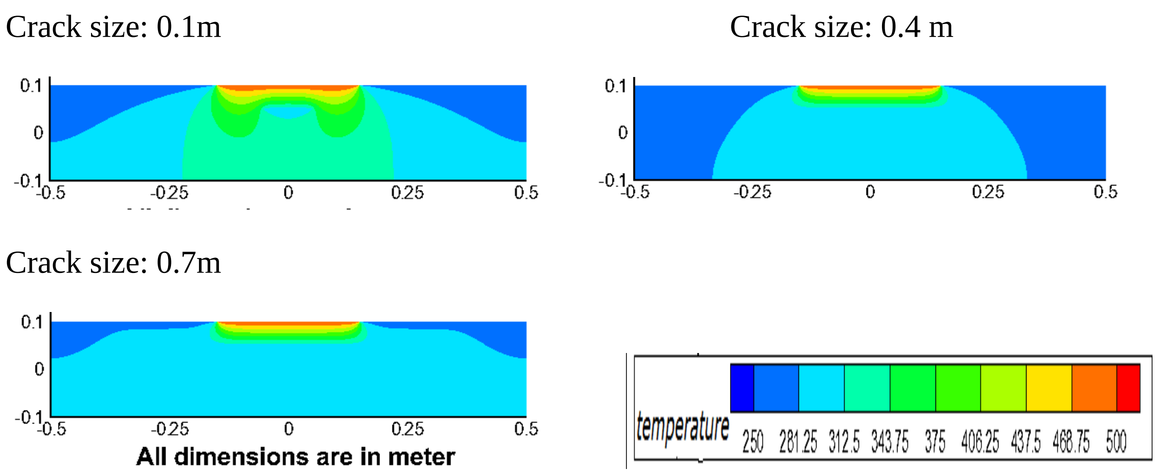


Figure 4.13: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.15 m from bottom edge for case-2.

Table 4.7: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.15 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-2(Data by treating crack as an Isothermal source).

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.15	0.3	0.1	308.2762	19.3618	0.0671	1.3706
0.15	0.3	0.2	293.6079	10.4708	-0.0407	1.3515
0.15	0.3	0.3	286.2113	7.3089	0.1342	1.4445
0.15	0.3	0.4	286.9728	7.3139	0.0669	1.4265
0.15	0.3	0.5	289.5375	7.0282	-0.1540	1.4394
0.15	0.3	0.6	292.1660	6.1318	-0.3834	1.5755
0.15	0.3	0.7	294.7173	4.6852	-0.6040	1.8247
0.15	0.3	0.8	297.0939	2.8366	-0.7988	2.1436
0.15	0.3	0.9	299.0723	0.9630	-0.9389	2.4327
0.15	0.3	1.0	300	0	NaN	NaN

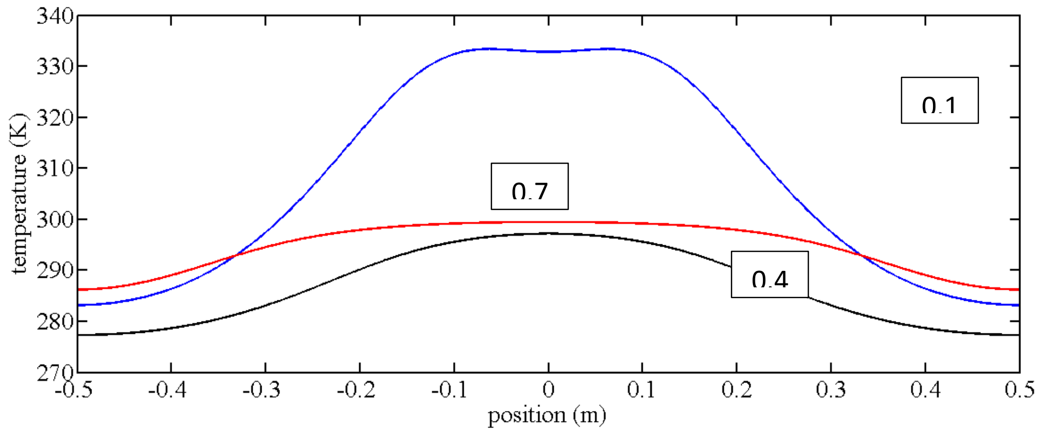


Figure 4.14: Position vs. temperature plot at bottom edge for figure 4.19.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.15m from the bottom edge is represented in figure 4.14.

4.1.2.4 Crack position: 0.175 m from the bottom edge

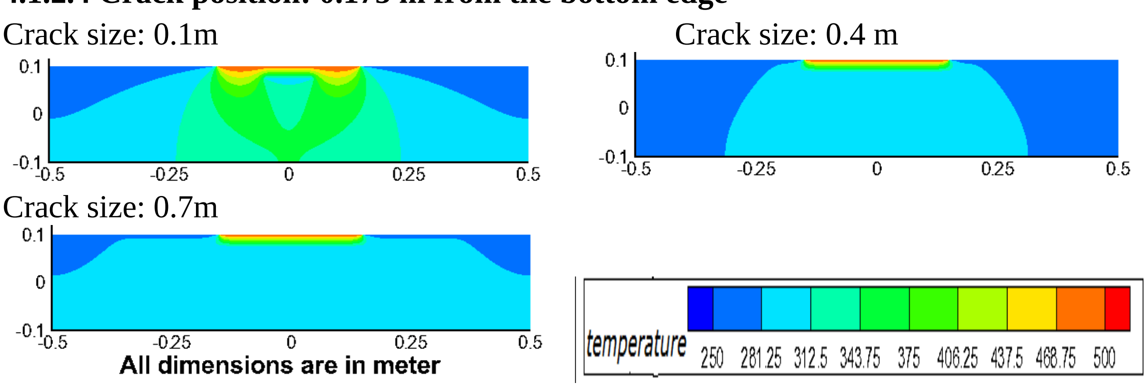


Figure 4.15: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.175 m from bottom edge for case-2.

Table 4.8: Temperature profile measured at the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.175 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-2. (Data by treating crack as an Isothermal source)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (at bottom edge) in terms of statistical parameters. Maintaining constant heat flux along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.175	0.3	0.1	312.2627	22.5749	0.1523	1.4204
0.175	0.3	0.2	294.6524	11.5326	0.0372	1.3738
0.175	0.3	0.3	283.9676	6.5331	0.2442	1.5086
0.175	0.3	0.4	285.6395	6.8010	0.1182	1.4517
0.175	0.3	0.5	288.3319	6.7474	-0.0904	1.4408
0.175	0.3	0.6	291.0064	6.0977	-0.2976	1.5322
0.175	0.3	0.7	293.6452	4.8852	-0.4925	1.7123
0.175	0.3	0.8	296.2065	3.1997	-0.6587	1.9392
0.175	0.3	0.9	298.5691	1.2775	-0.7721	2.1339
0.175	0.3	1.0	300	0	NaN	NaN

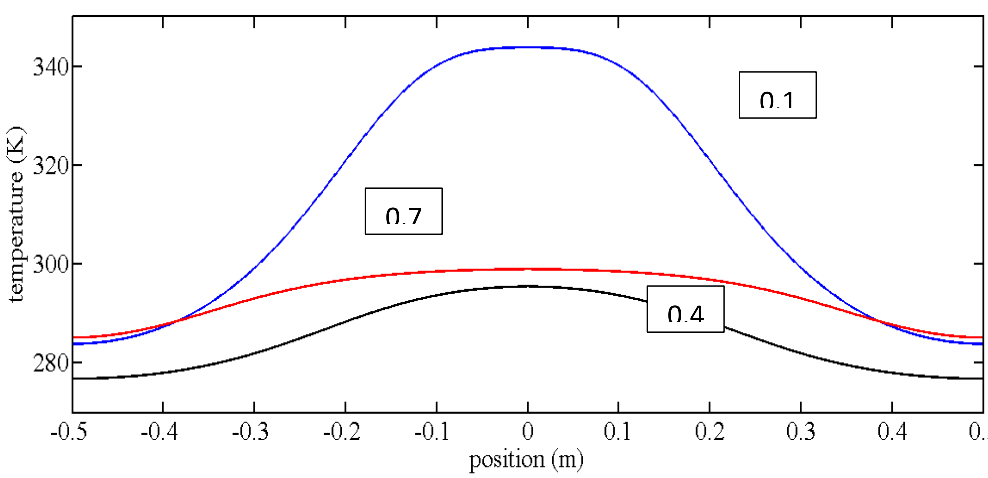


Figure 4.16: Position vs. temperature plot at bottom edge.

The temperature profiles at the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature and the bottom edge is specified with constant heat flux and the crack is placed at 0.1m from the bottom edge is represented in figure 4.16.

4.1.3 Case-3

In this case the bottom edge is treated as a media with constant temperature and the crack is treated as a media with zero heat flux.

The source temperature is fixed i.e. 500k and the side walls are assumed insulated. The crack is placed at 4 different positions relative to the bottom edge. The subcases are explained in the following sections with appropriate figures.

4.1.3.1 Crack position: 0.1m from the bottom edge

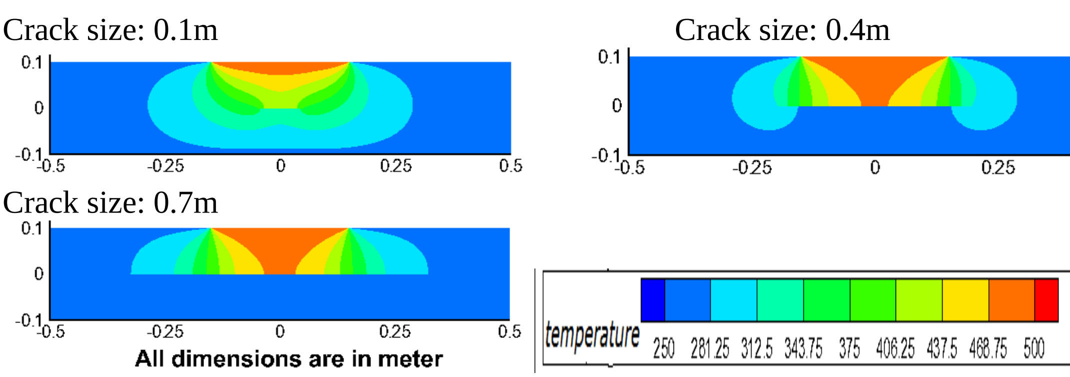


Figure 4.17: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.1 m from bottom edge for case-3.

Table 4.9: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.1 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-3.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.1	0.3	0.1	288.0017	14.2110	0.4346	1.5027
0.1	0.3	0.2	283.6533	9.1595	0.3742	1.6653
0.1	0.3	0.3	279.2437	5.0877	0.5657	1.9912
0.1	0.3	0.4	276.1382	2.5078	0.7141	2.1017
0.1	0.3	0.5	274.4685	1.1764	0.7269	2.1154
0.1	0.3	0.6	273.6737	0.5575	0.6085	2.0511
0.1	0.3	0.7	273.3077	0.2816	0.4677	1.7553
0.1	0.3	0.8	273.1404	0.1574	0.7141	1.7961
0.1	0.3	0.9	273.0635	0.0898	1.3656	3.3924
0.1	0.3	1.0	273	0	NaN	NaN

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with zero heat flux and the bottom edge is specified with constant temperature and the crack is placed at 0.1m from the bottom edge is represented in figure 4.18.

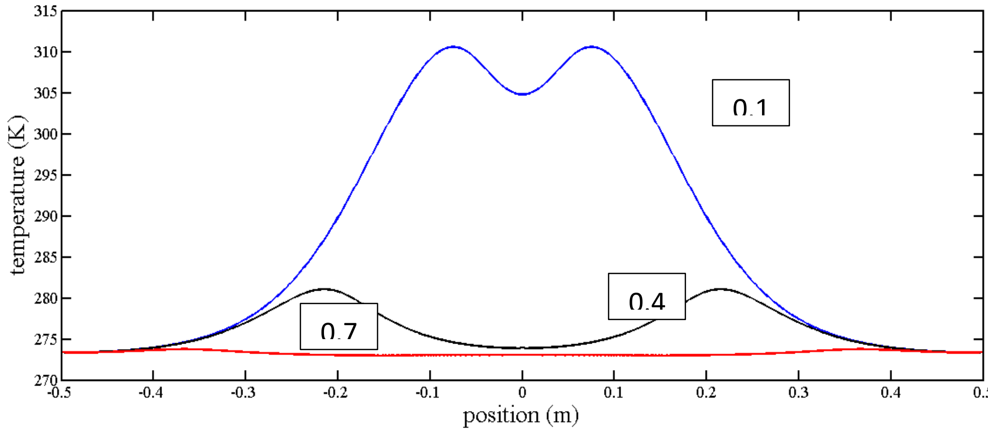


Figure 4.18: Position vs. temperature plot at a line 0.05 m above bottom edge from crack sizes of 0.1 m, 0.4 m, 0.7 m

4.1.3.2 Crack position: 0.125 m from the bottom edge

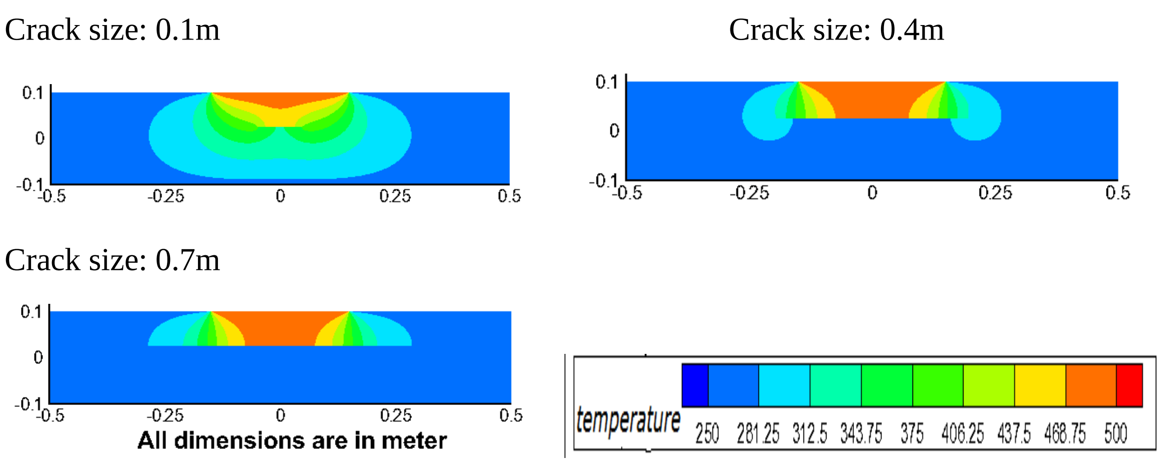


Figure 4.19: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.125 m from bottom edge for case-3.

Table 4.10: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.125 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-3.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.125	0.3	0.1	287.8523	14.1970	0.4580	1.5230
0.125	0.3	0.2	283.1060	8.5699	0.2244	1.3888
0.125	0.3	0.3	278.1656	3.8612	0.2140	1.6543
0.125	0.3	0.4	275.0322	1.3842	0.4178	1.8462
0.125	0.3	0.5	273.7270	0.4780	0.5563	1.8479
0.125	0.3	0.6	273.2560	0.1730	0.4449	1.8420
0.125	0.3	0.7	273.0901	0.0687	0.2530	1.5914
0.125	0.3	0.8	273.0319	0.0305	0.5206	1.5762
0.125	0.3	0.9	273.0115	0.0138	1.0956	2.7300
0.125	0.3	1.0	273	0	NaN	NaN

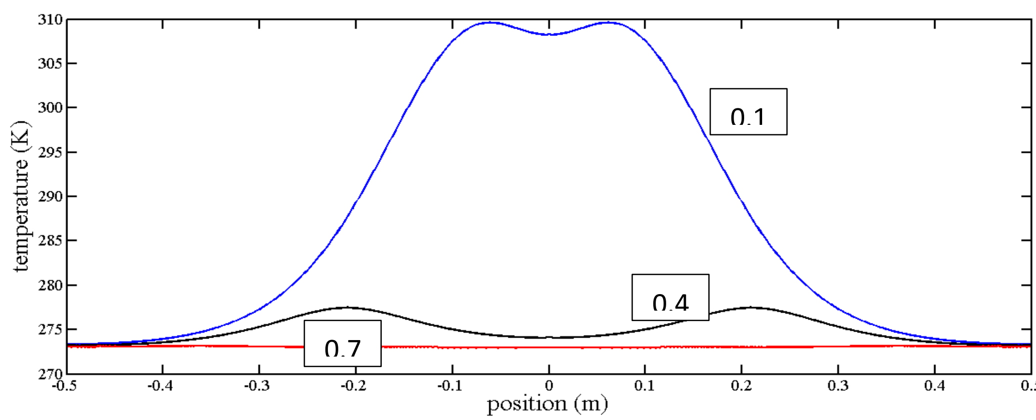


Figure 4.20: Position vs. temperature plot at a line 0.05 m above the bottom edge.

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with zero heat flux and the bottom edge is specified with constant temperature and the crack is placed at 0.125m from the bottom edge is represented in figure 4.20.

4.1.3.3 Crack position: 0.15m from the bottom edge

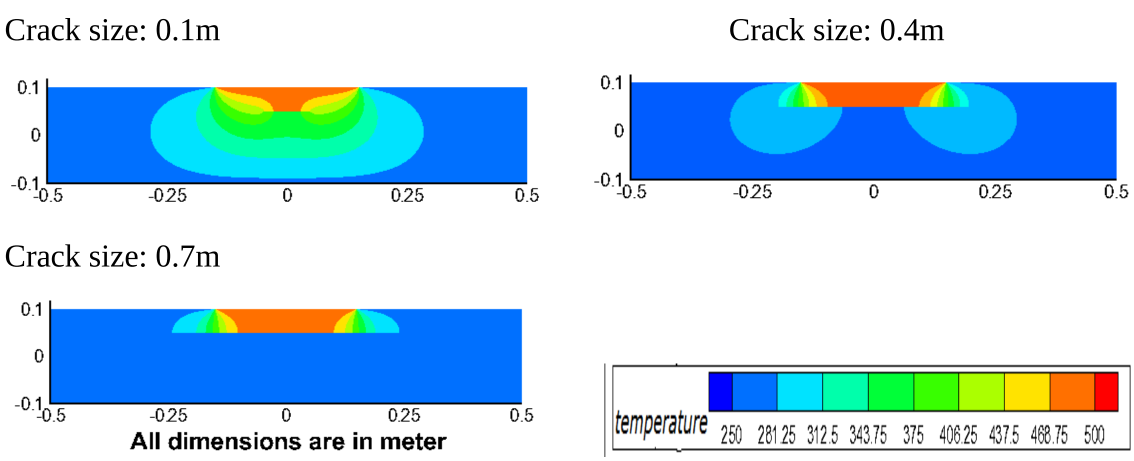


Figure 4.21: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.15 m from bottom edge for case-3.

Table 4.11: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.15 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-3.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.15	0.3	0.1	287.7644	14.2773	0.4967	1.5845
0.15	0.3	0.2	282.7345	8.4510	0.2421	1.3302
0.15	0.3	0.3	276.9888	2.9554	0.0183	1.3951
0.15	0.3	0.4	273.9502	0.5899	0.0614	1.7135
0.15	0.3	0.5	273.1999	0.1111	0.3525	1.7395
0.15	0.3	0.6	273.0417	0.0229	0.3821	1.7210
0.15	0.3	0.7	273.0087	0.0054	0.1315	1.5785
0.15	0.3	0.8	273.0018	0.0016	0.2577	1.4712
0.15	0.3	0.9	273.0003	4.7033e-04	0.7247	1.5251
0.15	0.3	1.0	273	NaN	NaN	NaN

From the table 4.11, it is observed that when the crack is placed at 0.15 m from the bottom edge, the mean temperature at the line 0.05 from the bottom edge does not change much. Skewness is positive for all the crack sizes.

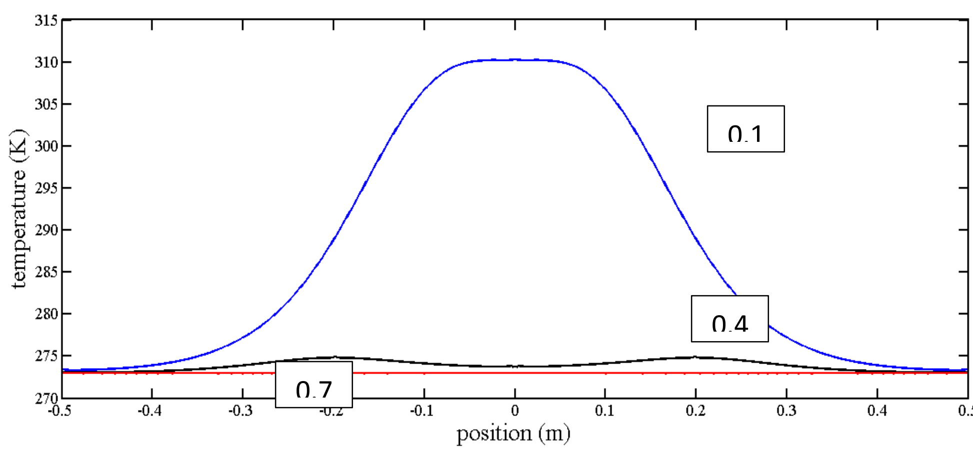


Figure 4.22: Position vs. temperature plot at a line 0.05 m above the bottom edge.

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with zero heat flux and the bottom edge is specified with constant temperature and the crack is placed at 0.15 m from the bottom edge is represented in figure 4.22.

4.1.3.4 Crack position: 0.175 m from the bottom edge

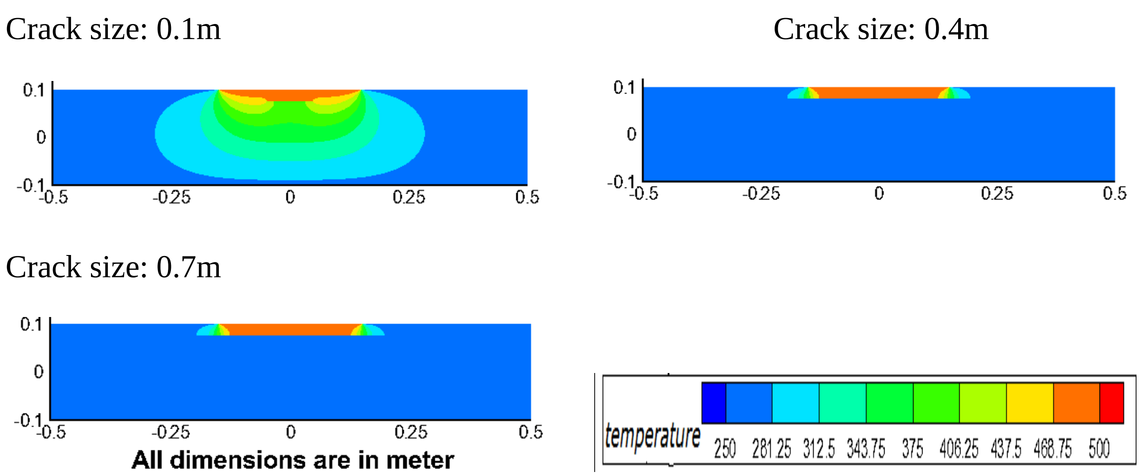


Figure 4.23: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.175 m from bottom edge for case-3.

Table 4.12: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.175 m from bottom-edge for crack sizes ranging from 0.1 m to 1.0 m for case-3.(Data by treating crack as an media with zero heat flux)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.175	0.3	0.1	287.8861	14.5598	0.5327	1.6435
0.175	0.3	0.2	282.8981	8.9333	0.3343	1.4027
0.175	0.3	0.3	275.6267	2.0522	0.0495	1.2711
0.175	0.3	0.4	273.1329	0.0821	-0.2003	1.5409
0.175	0.3	0.5	273.0058	0.0030	-0.0573	1.8015
0.175	0.3	0.6	273	0	NaN	NaN
0.175	0.3	0.7	273	0	NaN	NaN
0.175	0.3	0.8	273	0	NaN	NaN
0.175	0.3	0.9	273	0	NaN	NaN
0.175	0.3	1.0	273	0	NaN	NaN

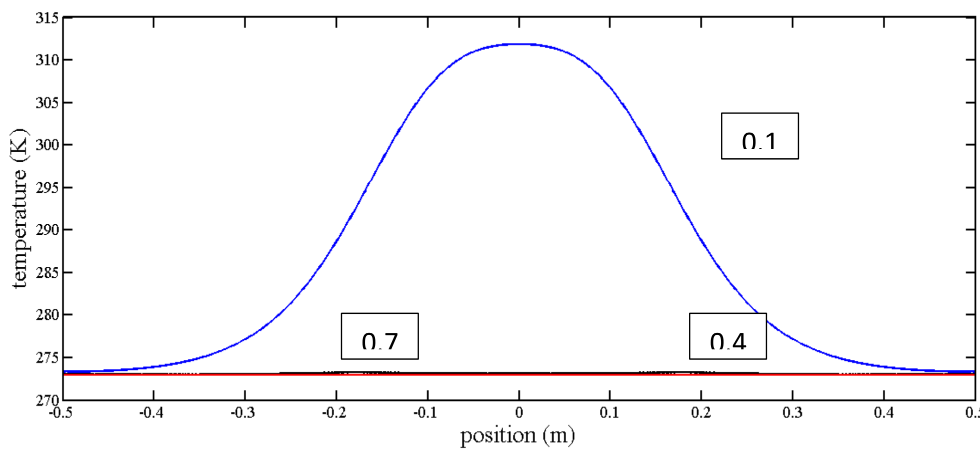


Figure 4.24: Position vs. temperature plot at a line 0.05 m above the bottom edge.

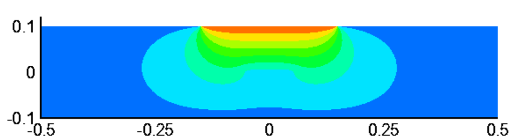
The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with zero heat flux and the bottom edge is specified with constant temperature and the crack is placed at 0.175 m from the bottom edge is represented in figure 4.24.

4.1.4 Case-4

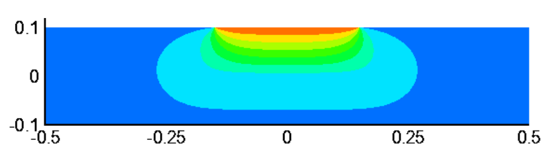
In this case the bottom edge is treated as a media with constant temperature and the crack is also treated as a media with constant temperature. The source temperature is fixed i.e. 500k and the side walls are assumed insulated. The crack is placed at 4 different positions relative to the bottom edge. The subcases are explained in the following sections with appropriate figures.

4.1.4.1 Crack position: 0.1m from the bottom edge

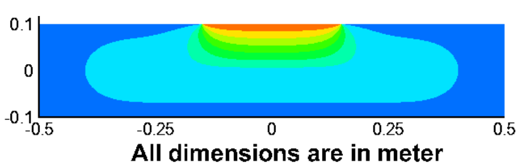
Crack size: 0.1m



Crack size: 0.4m



Crack size: 0.7m



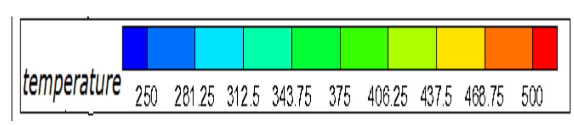


Figure 4.25: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.1 m from bottom edge for case-4.

Table 4.13: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.1 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-4. (Data by treating crack as an Isothermal source)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.1	0.3	0.1	283.4007	9.0802	0.2974	1.4558
0.1	0.3	0.2	280.7538	6.3334	0.1224	1.2908
0.1	0.3	0.3	279.5971	5.4021	0.1345	1.2821
0.1	0.3	0.4	279.9279	5.4573	0.0424	1.2455
0.1	0.3	0.5	281.0014	5.3871	-0.2577	1.2920
0.1	0.3	0.6	282.2868	5.9530	-0.6289	1.6387
0.1	0.3	0.7	283.6117	4.1001	-1.0581	2.4182
0.1	0.3	0.8	284.9036	2.7561	-1.5766	3.9058
0.1	0.3	0.9	286.0073	1.0292	-2.2057	6.5525
0.1	0.3	1.0	286.5000	0	NaN	NaN

From table 4.13 it is observed that when the crack is placed at 0.1 m from the bottom edge, the mean temperature at the line 0.05 m from the bottom edge remains very close to 273k. the standard deviation becomes zero for the crack size 1.0 m.

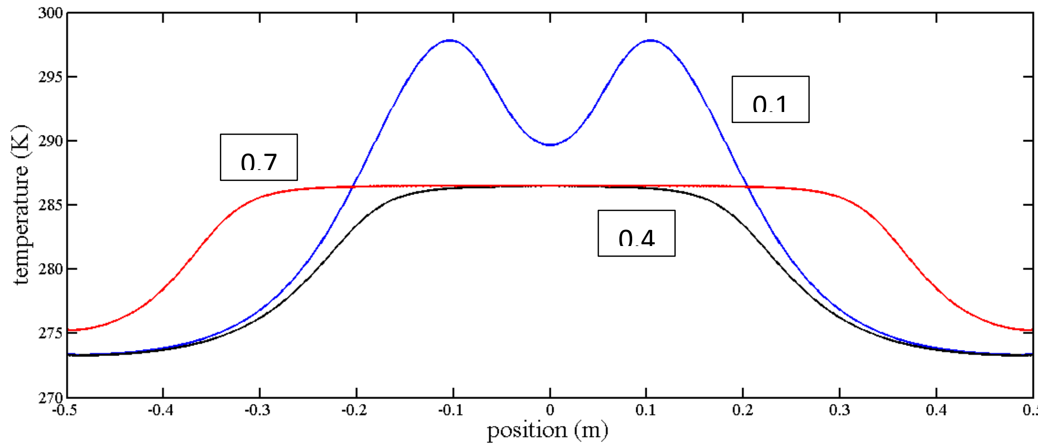


Figure 4.26**:** Position vs. temperature plot at a line 0.05 m above the bottom edge.

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature of 300k and the bottom edge is specified with constant temperature of 273k and the crack is placed at 0.1m from the bottom edge is represented in figure 4.26.

4.1.4.2 Crack position: 0.125 m from the bottom edge

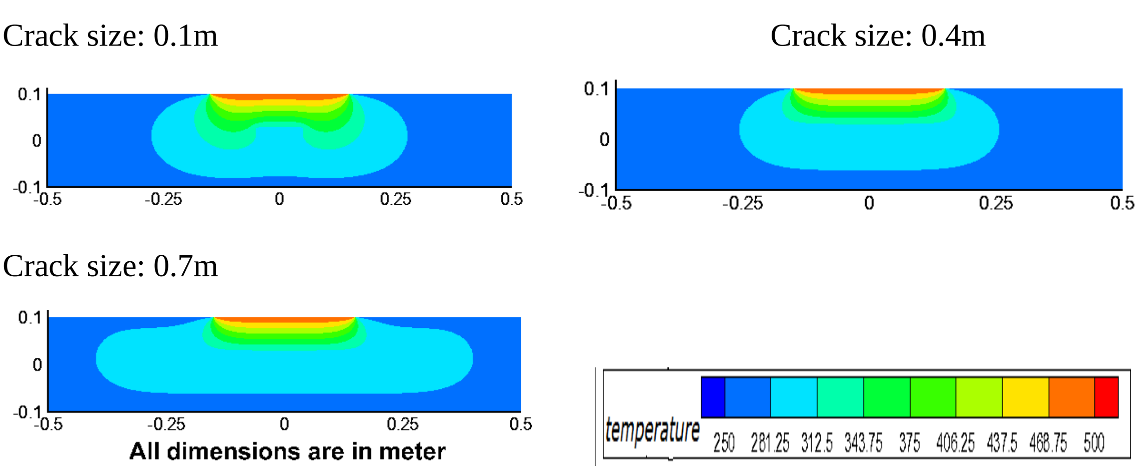


Figure 4.27: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.125 m from bottom edge for case-4.

Table 4.14: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.125 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-4. (Data by treating crack as an Isothermal source.)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge			
			Mean	Std	Skewness	Kurtosis
0.125	0.3	0.1	282.7417	8.4369	0.2607	1.3937
0.125	0.3	0.2	279.5744	5.3313	0.1117	1.2876
0.125	0.3	0.3	278.0826	4.2149	0.1784	1.3202
0.125	0.3	0.4	278.3649	4.2449	0.0818	1.2824
0.125	0.3	0.5	279.3147	4.1739	-0.2345	1.3206
0.125	0.3	0.6	280.3758	3.8133	-0.5963	1.6442
0.125	0.3	0.7	281.4453	3.1247	-0.9910	2.3291
0.125	0.3	0.8	282.4860	2.0620	-1.4248	3.4874
0.125	0.3	0.9	283.3868	0.7467	-1.8587	5.0900
0.125	0.3	1.0	283.8000	5.2891e-12	1	1

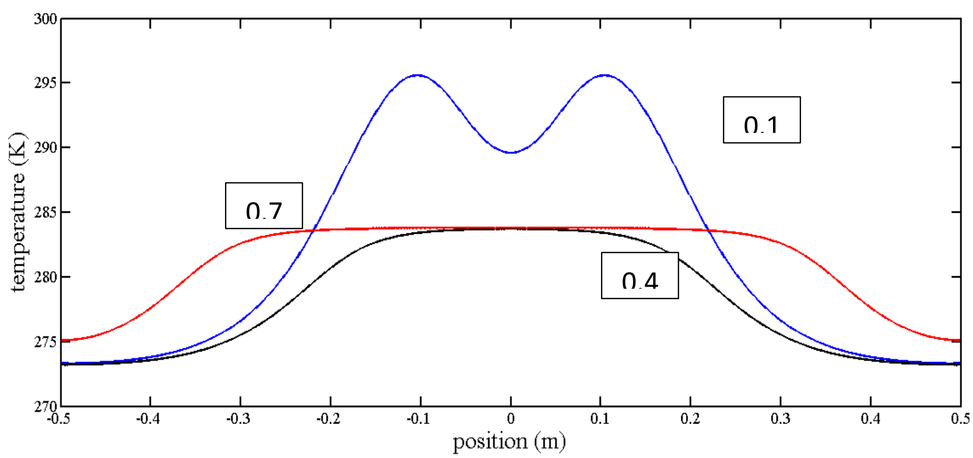
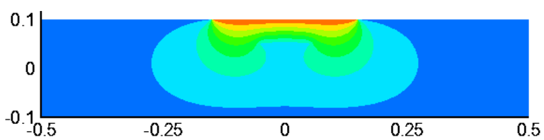


Figure 4.28: Position vs. temperature plot at a line 0.05 m above the bottom edge.

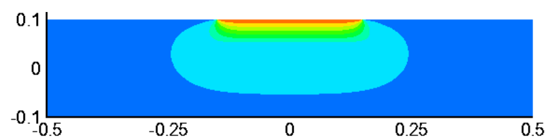
The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature of 300k and the bottom edge is specified with constant temperature of 273k and the crack is placed at 0.125 m from the bottom edge is represented in figure 4.28.

4.1.4.3 Crack position: 0.15 m from the bottom edge

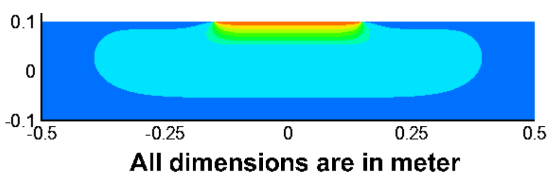
Crack size: 0.1m



Crack size: 0.4m



Crack size: 0.7m



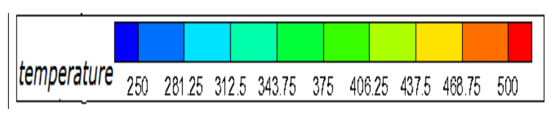


Figure 4.29: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.15 m from bottom edge for case-4.

From the above figure 4.29 it is observed that when the crack and the bottom edge both are specified with constant temperature, the temperature around the crack generally same. The temperature range figure given in the figure helps in predicting the range of temperature at a specific region. Table 4.15 shows the temperature at wall from 0.05 from bottom edge in terms of mean, standard deviation, skewness and kurtosis.

Table 4.15: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.15 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-4. (Data by treating crack as an Isothermal source.)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.15	0.3	0.1	282.6115	8.3784	0.2575	1.3564
0.15	0.3	0.2	278.8497	4.7759	0.1250	1.2859
0.15	0.3	0.3	276.9204	3.3773	0.2726	1.3943
0.15	0.3	0.4	277.2671	3.4239	0.1376	1.3260
0.15	0.3	0.5	278.1345	3.3807	-0.1933	1.3379
0.15	0.3	0.6	279.0317	3.0998	-0.5401	1.6156
0.15	0.3	0.7	279.9271	2.5519	-0.9002	2.1895
0.15	0.3	0.8	280.8057	1.7031	-1.2649	3.0714
0.15	0.3	0.9	281.5984	0.6399	-1.5805	4.0870
0.15	0.3	1.0	282	0	NaN	NaN

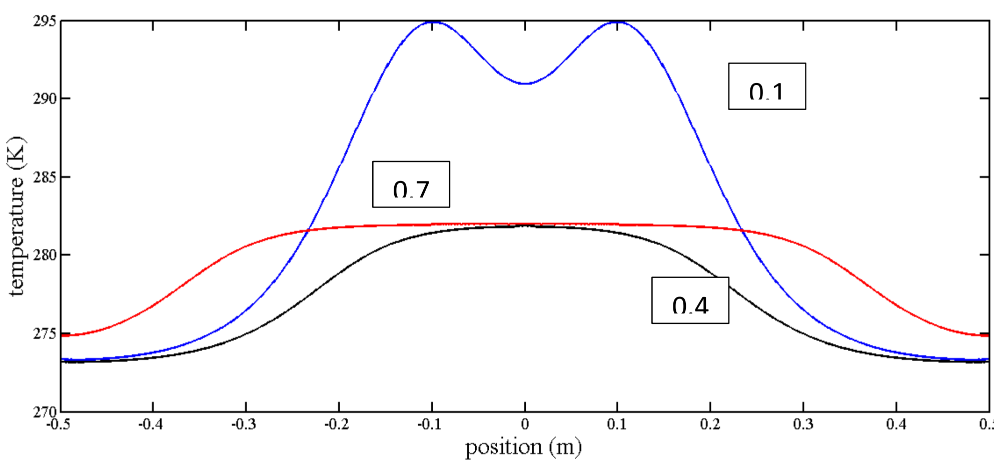


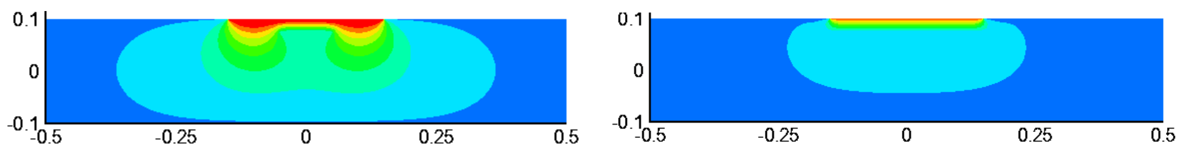
Figure 4.30: Position vs. temperature plot at a line 0.05 m above the bottom edge.

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature of 300k and the bottom edge is specified with constant temperature of 273k and the crack is placed at 0.15 m from the bottom edge is represented in figure 4.23.

4.1.4.4 Crack position: 0.175 m from the bottom edge

Crack size: 0.1 m

Crack size: 0.4m



Crack size: 0.7m

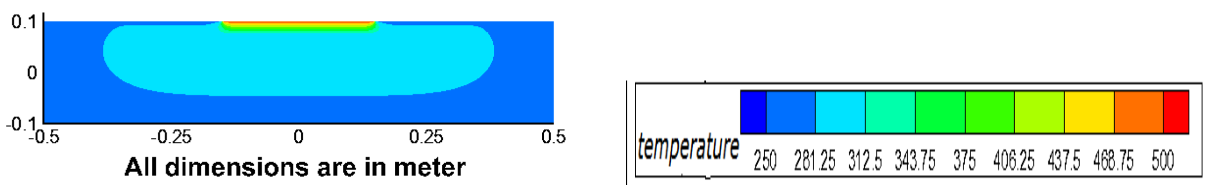


Figure 4.31: Temperature contours for crack size 0.1 m, 0.4 m, 0.7 m at crack position 0.175 m from bottom edge for case-4.

Table 4.16: Temperature profile measured at 0.05 m from the bottom edge in terms of mean, std, skewness and kurtosis for crack position at 0.175 m from the bottom edge for crack sizes ranging from 0.1 m to 1.0 m for case-4. (Data by treating crack as an Isothermal source)

Crack position (distance measured from bottom edge) (m)	High temperature Source size (m)	Crack length (m)	Output Temperature profile (0.05 m from bottom edge) in terms of statistical parameters. Maintaining constant temperature along bottom edge.			
			Mean	Std	Skewness	Kurtosis
0.175	0.3	0.1	283.1476	9.0384	0.2980	1.3680
0.175	0.3	0.2	278.7055	4.7392	0.1583	1.2929
0.175	0.3	0.3	275.9534	2.7064	0.4121	1.5265
0.175	0.3	0.4	276.4447	2.8195	0.1999	1.3762
0.175	0.3	0.5	277.2178	2.8275	-0.1277	1.3452
0.175	0.3	0.6	277.9885	2.6317	-0.4566	1.5579
0.175	0.3	0.7	278.7584	2.2121	-0.7876	2.0186
0.175	0.3	0.8	279.5227	1.5417	-0.1039	2.6922
0.175	0.3	0.9	280.2539	0.6547	-1.3513	3.3816
0.175	0.3	1.0	280.7140	3.5829e-12	-1	1

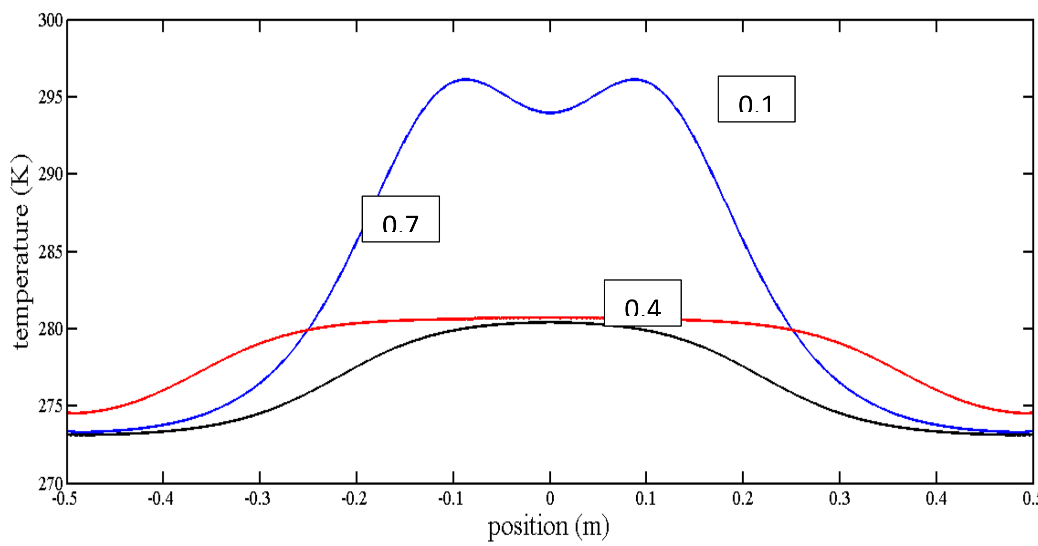


Figure 4.32: Position vs. temperature plot at a line 0.05 m above the bottom edge.

The temperature profiles at 0.05 m from the bottom edge for the crack sizes 0.1 m, 0.4 m and 0.7 m when the crack is specified with constant temperature of 300k and the bottom edge is specified with constant temperature of 273k and the crack is placed at 0.175 m from the bottom edge is represented in figure 4.32.

Chapter-5: Conclusions and scope for future work

5.1 Conclusions

- The temperature profiles are obtained for different boundary conditions of the crack and bottom edge as mentioned before.
- The temperature plots are drawn at the bottom edge as well as a line located at 0.05m above the bottom edge.
- When the crack length becomes larger than the source length, then the skewness of the temperature plots gradually decrease in most of the cases.
- When the crack approaches towards the source, the solution converges more rapidly i.e. it becomes difficult to find difference between the various contours.

5.2 Scope for future work

- The future work may be carried out by changing the thermal conductivity for various materials.
- A attempt could be done to predict the shape and size of crack using the results by using a neural network.
- The investigation of heat conduction process in a homogeneous solid could be done by exposing the slab towards multi heat source instead of a single source.

REFERENCES:

Clements,D.L., 1979, stationary heat conduction in an anisotropic slab containing a crack, *Applied engineering and science* 17: 1141-1149.

Milosevic,N.D., Raynaud,M., 2003**,** Analytical solution of transient heat conduction in a two-layer anisotropic cylindrical slab excited superficially by a short laser pulse, *International journal of Heat and Mass transfer*, 47: 1627–1641.

Ang,W.T., Yun,B.I., 2011 ,A complex variable boundary element method for axisymmetric heat conduction in a nonhomogeneous solid, *Applied Mathematics and Computation* 218: 2225–2236.

Shiah,Y.C., Shi,Y., 2006 , Heat conduction across thermal barrier coatings of anisotropic substrates, *International Communications in Heat and Mass Transfer* 33: 827–835.

Shiah,Y.C., Shi,Y., 2006, Anisotropic heat conduction across an interface crack/defect filled with a thin interstitial medium, *Engineering Analysis with Boundary Elements* 30: 325–337.

Yun,I.B., Ang,T.W., 2010, A dual-reciprocity boundary element approach for axisymmetric nonlinear time-dependent heat conduction in a nonhomogeneous solid , *Engineering Analysis with Boundary Elements* 34: 697–706.

Knupp,C.D., Naveira-Cotta,P.C., Cotta,R.M., 2012 , Theoretical experimental analysis of heat transfer in nonhomogeneous solids via improved lumped formulation, integral transforms and infrared thermography, *International Journal of Thermal Sciences* 62: 71-84.

Hutchinso,W.J., 2008 , laminate delamination due to thermal gradients, *Division of applied sciences, Havard University, Cambridge*, MA02138.

Ristovski,D.Z., Dramic'anin,M.D., 1998, Conduction of heat in inhomogeneous solids, Applied physics letters 73(3).

Zhou,H., Zhang,S., Yang,M., 2007, The effect of heat-transfer passages on the effective thermal conductivity of high filler loading composite materials. *Computational Science and Technology,* 67:1035–40.

Salt,H., 1983, Transient conduction in a two-dimensional composite slab–I. Theoretical development of temperature modes, *International journal of Heat Mass Transfer 26* (1983) 1611– 1616.

Salt,H., 1983, Transient conduction in a two-dimensional composite slab–II. Physical interpretation of temperature modes, *International journal of Heat Mass Transfer* 26: 1617–1623.

Shiah,Y.C., Tan, C.L., 1998, BEM Treatment of two-dimensional anisotropic field problems by direct domain mapping, Engineering Analysis with Boundary Elements, Elsevier Science Ltd, 20: 347–351.

Chien-Ching Ma, Shin-Wen Chang., 2004, Analytical exact solutions of heat conduction problems for anisotropic multi-layered media, *International Journal of Heat and Mass Transfer* 47: 1643–1655.

N.D. Milo_sevi_c, M. Raynaud, K.D. Magli_c., 2003, Simultaneous estimation of thermal diffusivity and thermal contact resistance of thin solid films and coatings using the twodimensional flash method, *International journal of Thermophys.* 24 (3): 799–819.